EVALUATION AND TESTING OF RELATIVE HUMIDITY SENSORS

David M. Schwenk
CECER-FLE
800-USA-CERL x7241
217-373-7241

BACKGROUND

Accurate measurement of humidity is important in many heating, ventilating, and air-conditioning (HVAC) applications. Maintaining a specified room or space humidity can be critical in laboratories, clean rooms, hospital operating rooms, museums, and archaeological preservation facilities. In these buildings, humidification is usually provided by injecting moisture into an air duct that distributes the humidified air to the building spaces. To prevent condensation from forming in the duct, humidity should also be measured and controlled immediately downstream of the moisture injection mechanism. In the above applications, accurate measurement and control of humidity can be crucial to occupant health and to the equipment and contents of the building.

INTRODUCTION

Two common types of commercial grade, room wall-mount, relative humidity (RH) sensors were evaluated: resistive and capacitive. In addition to basic comparisons, the sensors were tested for accuracy and long term (drift) performance. Three of each type were purchased, all from separate manufacturers. Each was specified to have an accuracy of ±3% RH over a nominal range of 20-80% RH. Four were provided with a drift rate specified not to exceed 1% RH per year.

EVALUATION OF SENSORS

Relative humidity is a measure of the amount of water in the air at a given temperature. There are several sensor technologies available to measure relative humidity. The two most popular ones, probably due to their low cost, use a capacitive or resistive sensing element. The ASHRAE Applications handbook refers to these as electronic hygrometers.

Relative humidity sensors consist of an integrated sensor and transmitter assembly. The sensor provides a measure of the relative humidity while the transmitter generates an electronic output signal representative of the sensed humidity.

The resistance type of sensor uses a conductive grid coated with a hygroscopic substance. The conductivity of the grid varies with water retained thus the resistance varies with humidity. The conductive element is arranged in an alternating current-excited wheatstone bridge. The electronic circuitry provides temperature compensation and linearizes the resistance signal to provide an output signal as the relative humidity changes from 0 to 100%. ASHRAE Applications Handbook indicates that the resistive type responds quickly to humidity changes. Brownawell indicates that the response time is relatively slow as it may take tens of seconds or even minutes for changes in humidity to fully affect the resistance readings.

The capacitance type of sensor contains a stretched membrane of nonconductive film, with metal electrodes on both sides, mounted within a perforated plastic capsule. The change in the sensor's capacitance is nonlinear with respect to rising relative humidity. The signal is linearized and compensated for temperature in the amplifier circuit to provide an output signal as the relative humidity changes from 0 to 100%. Brownawell indicates that the response time is fast, but varies depending on the construction of the sensor.

Twenty sensor vendors were located in the annual "Products" issue of Heating, Piping, and Air-Conditioning magazine. Due to the nature of this source, and that all vendors described or advertised their sensors as being intended for use in HVAC applications, the sensors are classified as "commercial" grade.

Of the twenty vendors, nine offered capacitive sensors, four offered resistive, six did not offer any, and one did not know what type theirs was.

Table 1 shows the specifications for the sensors that were selected for testing, in addition to the sensor costs which ranged from just over $100 up to $250. Some may be at government discount.

Relative humidity sensors must respond to both moisture and temperature, but only three manufacturers provided a temperature effect specification. Table 1 shows that the specifications ranged from 0.005 %RH/^{o}F to 0.02 %RH/^{o}F. The later would result in an error of 1% RH over a 50°F temperature range. Temperature effect was not investigated in the experiment as all data was taken at a constant temperature.

TABLE 1. RELATIVE HUMIDITY SENSOR SPECIFICATIONS.

Ref. Number:	RESISTIVE SENSORS			CAPACITIVE SENSORS		
	RH-1	**RH-2**	**RH-3**	**RH-4**	**RH-5**	**RH-6**
Vendor Name Part Number	General Eastern RH-3	Elan Technical Corporation (ETC) HT 1010	Temperature Control Specialties (TCS) TH 1020	Hy-Cal CT 829 A-MH	Mamac HU-225-3-ma	Vaisala HMW 40 U
Cost	$225	$140	$111	$205	$256	$158
Accuracy	3% (20-95%RH)	3% (10-95%RH)	3% (20-95%RH) at 25°C	3% (0-90%RH) 59 to 120°F	3% (20-80%RH) NIST traceable	3% (10-90%RH)
Repeatability	incl. 0.5%RH	0.5%RH	0.5%RH	included	0.25%	
Stability	1% RH/yr	1% RH/yr	1% RH/yr			1% RH/yr
Hysteresis	incl. 1%			included	0.25%	
Temperature Effect	0.06%/°F			included	0.005%/°F	< 0.02%/°F -10 to 60°C
Voltage Effect		0.002% RH/vdc	0.003% RH/vdc	0.002 RH/vdc		
Sensitivity	0.1% RH				0.01%	
Operating Range (°F)	-40 to 130°F	0 to 160°F	-15 to 170°F	-4 to 150°F	-40 to 135°F	23 to 131°F
Time Constant			20 sec. - still air (30 to 80 %RH)	50 sec. in slow air	10 seconds (for 90% RH)	

Zero & Span Adjustment	yes	yes	yes	yes	yes	yes
Maintenance notes			interchange accuracy 5%	wash	wash	None. Change sensor
Other				monolithic CMOS i.c. w/capacitive thin film	solid state polymer capacitance	thin film capacitive solid state

"Included" means that the specification is included in the "Accuracy" specification.

Capacitive sensors tend to be inaccurate at high humidities due to saturation of the sensing element and resistive sensors tend to be inaccurate at very low humidities (Brownawell). The specifications in Table 1 appear to support this. This suggests that the resistive type is the better choice for use in a duct high-limit humidity control application where humidity is measured and controlled downstream (usually about 10 feet) of a humidifier.

Resistive sensors are particularly resistant to surface contamination (Brownawell, Weisman) because contaminants cannot penetrate the polymer. This can be advantageous in duct humidity measurement applications where, in spite of filtering, the air can be dirty.

Three of the six sensor manufacturers in Table 1 provided a transient response specification. The range is from 10 to 50 seconds. Transient response of the sensor is not very important in room humidity measurement and control applications, but in the a duct high-limit application speed of response can be crucial. A long response time might result in saturation of the duct.

Manufacturer literature did not indicate at what intervals calibration might be required. Several manufacturers recommended cleaning of sensors at periodic, but unspecified, intervals. Cleaning can be accomplished with distilled water or isopropyl alcohol. Two manufacturers indicate that the sensing element can be readily replaced.

TEST METHOD AND APPARATUS

Test Method

The three resistive and three capacitive sensors listed in Table 1 were tested at approximately 30, 40, and 50% RH and at a constant temperature of 68.8^{o}F (plus or minus less than 0.5^{o}F).

At each of the three humidity levels, after reaching steady state, five measurements were obtained from each sensor in random order over about a five minute period. This defined a data set. Data sets were taken once a week for 8 weeks, then monthly through the fourth month, then every other month through the first year. A recent data set was taken after nearly two years since the experiment began.

Test Apparatus

The tests were conducted in a 12x15x8 foot room. To help minimize moisture loss, the test room was partially sealed using plastic drop cloth. Humidity level was established using two residential grade humidifiers and a dehumidifier. Temperature was maintained using oil filled radiant and electric strip heaters.

Sensor error was determined by comparing each sensor reading to a chilled mirror dew point sensor (with NIST traceable calibration accuracy of ±0.5% RH).

Sensor readings were obtained by measuring the voltage drop across a precision 499 ohm output resistor. Resistances and voltages were measured using a precision multimeter (±0.12% of reading).

Air movement across the sensors was achieved using a residential box fan, running on low speed, located approximately 5 feet in front of the sensor rack. The fan was run only while taking data.

TEST RESULTS

General

During initial testing two of the capacitive sensors were found to be defective. RH-5 was providing an output that was in error by about 20-25% RH. The output of RH-4 was oscillating at a rapid frequency (approximately 1 Hz). The peak-to-peak magnitude of the oscillation was about 0.7% RH, but the sensor was otherwise accurate. Both units were replaced and RH-5 was still not within the specified accuracy but was significantly closer so it was used in experiment.

The experiment officially began on 23 Dec 1995. All sensors were tested in their original (as supplied from the vendor) condition. No calibrations were attempted prior to or during the experiment.

Analysis of Variance

An analysis of variance (ANOVA) was performed on the eight data sets covering the first eight weeks of the experiment. The ANOVA indicated that (in order of significance);

- There is a very large variance between the accuracies of the individual sensors within the two Categories (resistive and capacitive). This suggests that the resistive sensors are not of equivalent accuracy and that the same can be said about the capacitive sensors.

- There is a relatively large variance in sensor accuracy as a function of Time. While this might suggest that the sensors drift, examination of the raw data showed no clear pattern of drift. Therefore we conclude that the RH sensors do not provide repeatable readings, but the magnitude of the non-repeatability is not especially large. The average standard error of estimate ranged from 0.2 to 0.9% RH for the six sensors. (The standard error of estimate for each sensor is shown in Table 3.)

- There is a moderate variance in the interaction between Time and sensor Category (resistive and capacitive) suggesting that the two categories of sensors do not have the same repeatability.

- There is some variance in the category of sensor (resistive and capacitive) suggesting that the two categories are not of equivalent accuracy.

- There is a small variance in the interaction between time and the sensors nested in Categories (resistive and capacitive). This suggests that there are no individual sensors that are less repeatable than others.

RMS Error

Table 2 shows the root-mean-square (RMS) error of each sensor based on the first 8 weeks of data. Two resistive sensors and one capacitive sensor is producing the manufacturer specified ±3% accuracy. Neither Category of sensor (resistive or capacitive) is producing the specified accuracy, nor is the whole group of sensors. The purchase price of each sensor is also shown in the Table. Some may be at government discount. Note that there appears to be little to no correlation between sensor accuracy and cost.

Table 2. Initial Accuracy of Wall-Mount RH Sensors.

	Cost	**Individual** RMS Error (%RH)	**Category** RMS Error (%RH)	**Group** RMS Error (%RH)

<table>
<tr><td>Resistive-1 (RH-1)</td><td>$225</td><td>± 1.1%</td><td rowspan="3">± 4.0%</td><td rowspan="6">± 3.6%</td></tr>
<tr><td>Resistive-2 (RH-2)</td><td>$140</td><td>± 1.2%</td></tr>
<tr><td>Resistive-3 (RH-3)</td><td>$111</td><td>± 6.7%</td></tr>
<tr><td>Capacitive-1 (RH-4)</td><td>$205</td><td>± 0.5%</td><td rowspan="3">± 3.2</td></tr>
<tr><td>Capacitive-2 (RH-5)</td><td>$256</td><td>± 4.3%</td></tr>
<tr><td>Capacitive-3 (RH-6)</td><td>$158</td><td>± 3.4%</td></tr>
</table>

Linear Regression

A least squares linear regression was performed for each sensor using the 8 data sets from the first 8 weeks of data to further assess sensor accuracy. The regressions were computed from the data taken at 30, 40 and 50% RH. Regression results provide a point slope equation for each sensor:

$$y = mx + b \qquad \text{Eqn. 1}$$

Table 3 shows the regression results. An ideal "b" (y intercept) is 0% RH and an ideal "m" (slope) is 1.00 %RH/%RH. Table 3 also shows the estimated (worst case) sensor error over a range of 30-50% RH and over an extrapolated range of 0-100% RH. The 0-100% prediction is extrapolated because the least squares regression is based on data taken over a 30-50% RH range.

Table 3. Least Squares Linear Regression (first 8 weeks of data). Estimated sensor output = m * (actual RH) + b

	"b" (RH)	"m" (RH/RH)	standard error of estimate (%RH)	estimated error (30-50% range) (%RH)	Extrap. error (0-100% range) (%RH)
Resistive-1 (RH-1)	0.5	1.01	0.7	1.1	2.3
Resistive-2 (RH-2)	2.8	0.95	0.5	1.6	4.9
Resistive-3 (RH-3)	-6.8	1.00	0.9	7.3	9.9
Capacitive-1 (RH-4)	0.4	0.99	0.2	0.5	1.7
Capacitive-2 (RH-5)	4.5	1.00	0.7	4.8	6.6
Capacitive-3 (RH-6)	1.4	1.05	0.4	3.8	6.3

The y intercept and slope are adjustable using the zero and span adjustments, respectively, on the transmitter. With either of the worst case spans (0.95 and 1.05), if the sensor were calibrated at mid span (50% RH), which generally is an easy condition to establish in HVAC, and only a zeroing adjustment were made to calibrate the sensor, theoretically it could be adjusted to be accurate to within ±2.5% of the entire span of the sensor. This suggests that a single-point calibration can bring a worst case sensor to within its specified accuracy. In fact, with the gain within ±0.05 (which is the case for all sensors tested in this experiment), a single-point zero-adjustment calibration will bring the sensor to within the specified ±3% RH accuracy if the sensor is calibrated anywhere within the range of 40 to 60% RH.

Sensor Drift

Four of the six sensors were specified to have a drift rate not to exceed 1% RH per year. The other two sensors did not have a drift specification. Drift was assessed by comparing sensor performance after one year and after one year 11 months to the first data set. The results are shown in Table 4.

Only one sensor has a drift rate in excess of 1% RH/year. Both the resistive and capacitive sensor categories and all sensors as a group drift less than 1% RH/year. These results are much better than those reported in the Mechanical Engineering Newsletter for Military Programs (Aug 96) which were based on 6 months of data.

Table 4. Drift (%RH/year) of Wall-Mount Relative Humidity Sensors.

	After 1 yr.	After 1 yr. and 11 mo.	**Individ.** Avg.	**Category** Avg.	**Group** Avg.
Resistive-1 (RH-1)	-0.1	0.6	0.2	0.5	0.6
Resistive-2 (RH-2)	0.7	0.1	0.4		
Resistive-3 (RH-3)	-0.2	1.9	0.9		
Capacitive-1 (RH-4)	2.5	1.7	2.1	0.8	
Capacitive-2 (RH-5)	-0.6	0.5	-0.0		
Capacitive-3 (RH-6)	-0.1	0.6	0.3		

Time Line Plots

A least squares linear regression was performed for each sensor using all data sets to date. Time line plots of the predicted sensor output at an actual (desired) value of 40% RH are shown in figures 1 through 6.

Experimental Bias

The intent of the sensor purchases was not revealed to any vendor. Due to the length and detail of the discussions with the vendors who supplied sensors for the evaluation (in an attempt to obtain as much information as possible), it is possible that one or more may have suspected the intent our sensor purchase. Capacitive sensor RH-6 was purchased from the same vendor and through the same person as was the "true" reading chilled mirror device, although they were purchased at separate times.

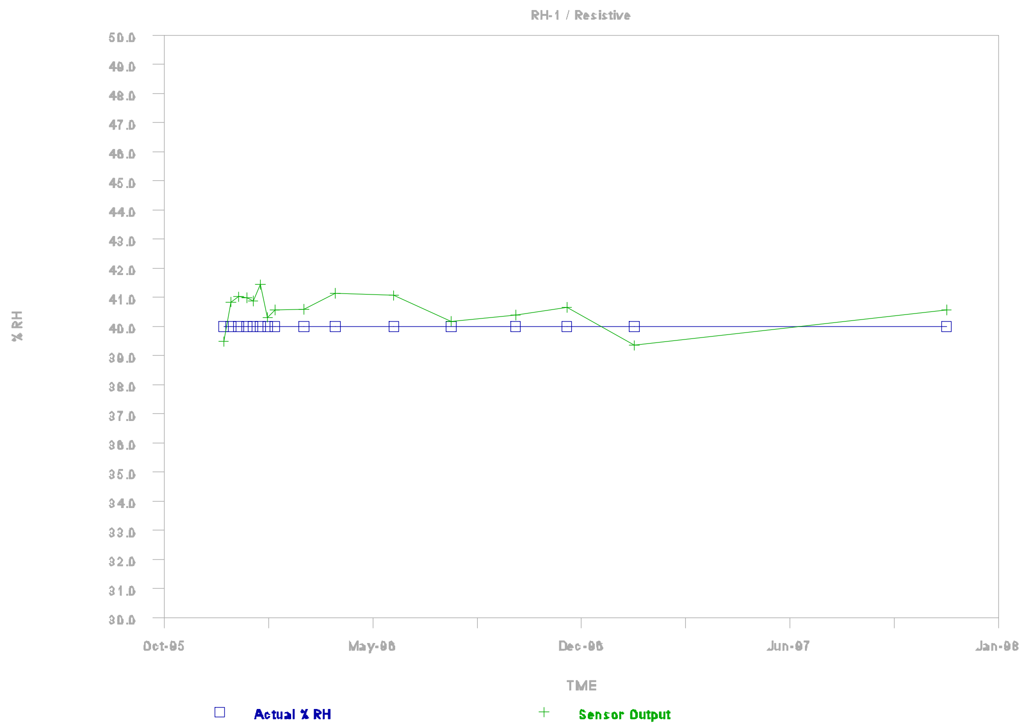

Figure 1. Resistive Sensor RH-1 Accuracy at 40% RH.

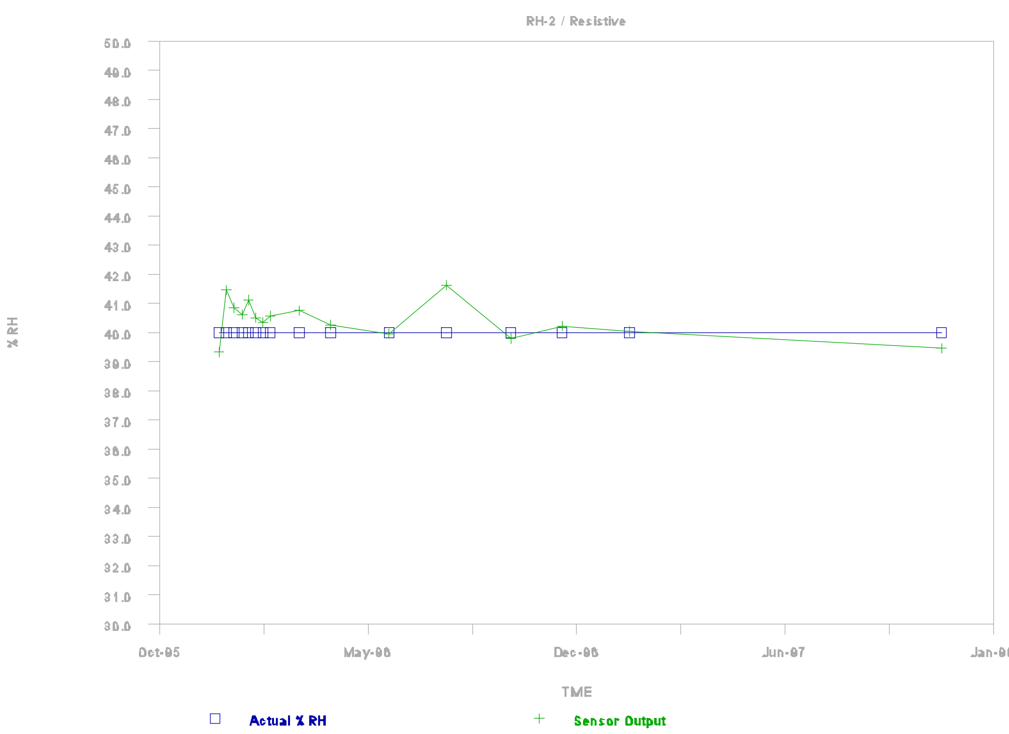

Figure 2. Resistive Sensor RH-2 Accuracy at 40% RH.

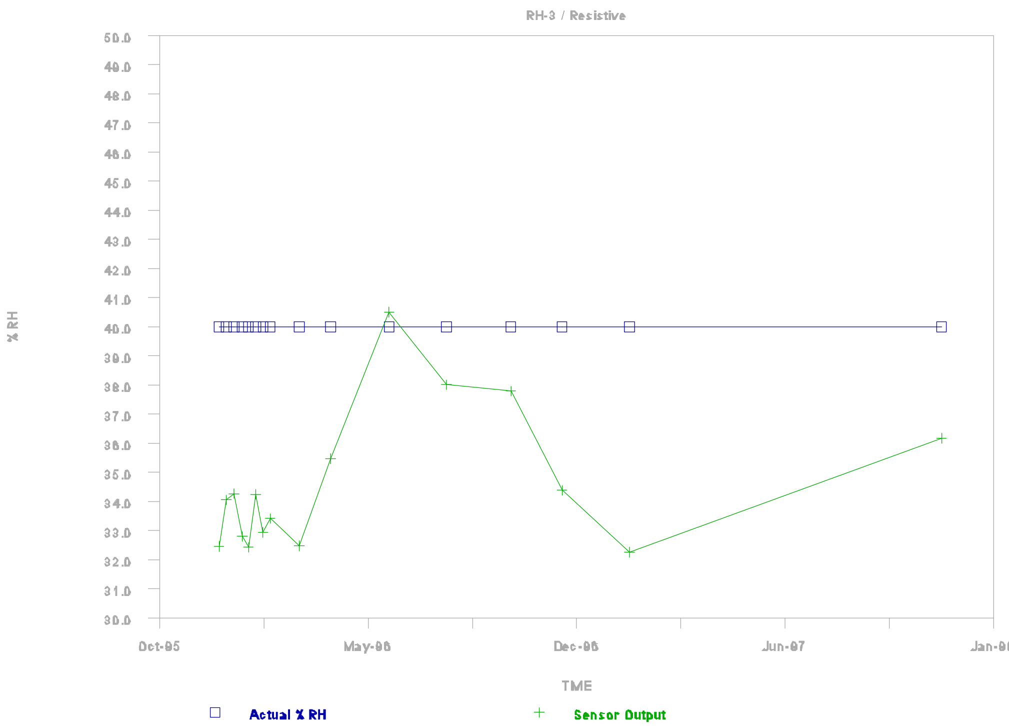

Figure 3. Resistive Sensor RH-3 Accuracy at 40% RH.

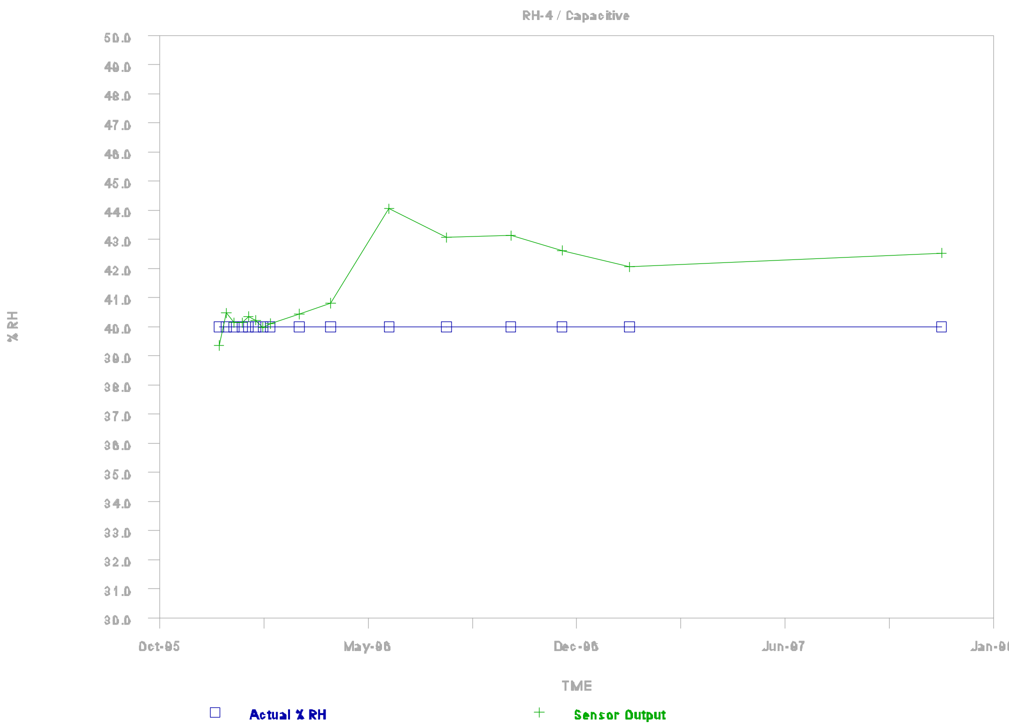

Figure 4. Capacitive Sensor RH-4 Accuracy at 40% RH.

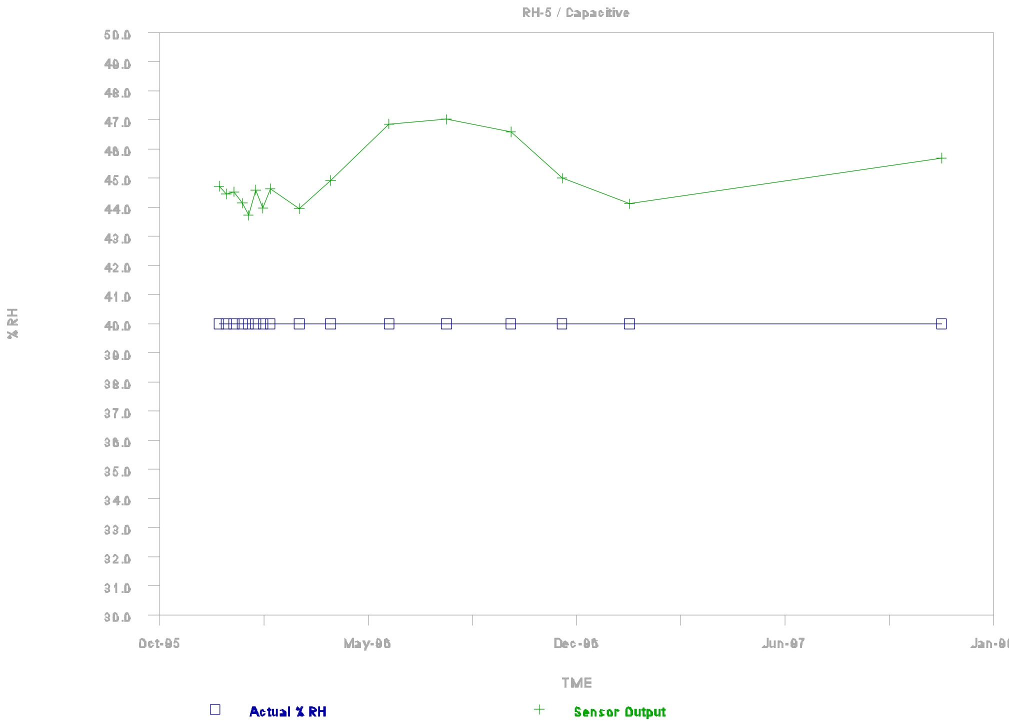

Figure 5. Capacitive Sensor RH-5 Accuracy at 40% RH.

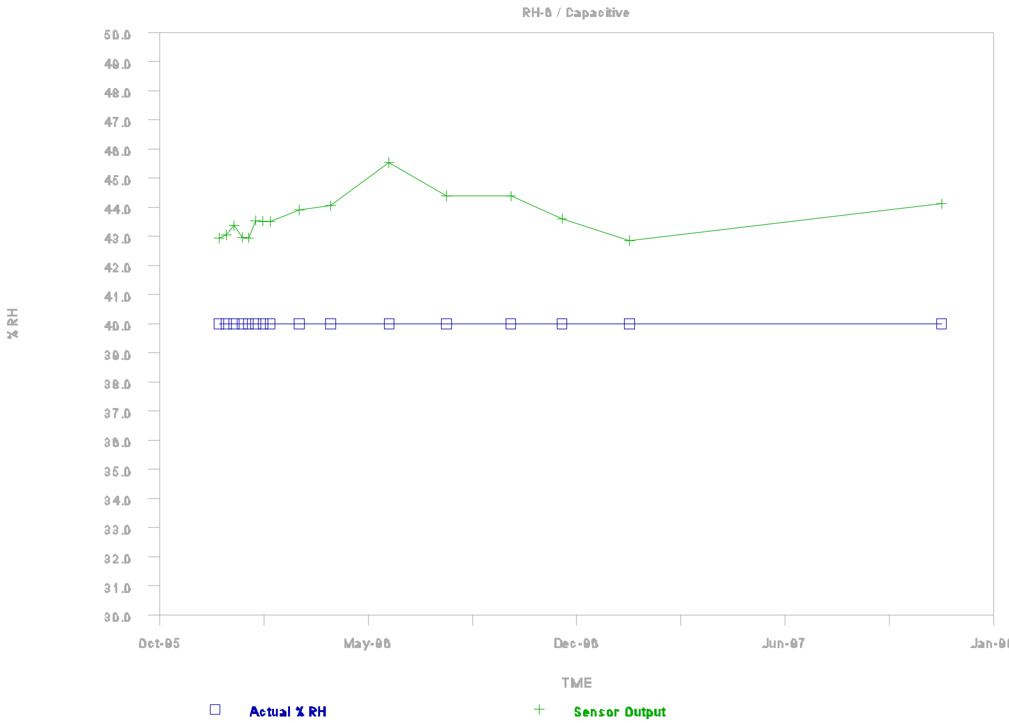

Figure 6. Capacitive Sensor RH-6 Accuracy at 40% RH.

CONCLUSIONS AND RECOMMENDATIONS

The evaluation of relative humidity sensor accuracy reported here is constrained to wall mounted sensors and although the sensing technology is essentially the same, different results might be obtained for duct mounted sensors exposed to higher air velocities in a dirtier environment.

As a group, resistive and capacitive sensors do not meet the specified ±3% accuracy, nor do the individual (capacitive or resistive) categories, although the resistive group fared better. Individually, three of six sensors (two resistive and one capacitive) met the specified accuracy. A capacitive sensor had the best error at ±0.5% RH. A resistive sensor had the worst at ±6.7% RH.

All the tested sensors have zero and span adjustments. The data indicates that a single-point zero-adjustment calibration is all that may be required to bring a sensor to within the specified ±3% RH accuracy over a 0-100% RH range (no span adjustment is required) as long as the point at which the calibration is performed is within the range of 40-60% RH. This conclusion is somewhat of an extrapolation as it is based on experimental data taken within a range of 30-50% RH.

As a group, the resistive and capacitive sensors drifted only 0.6% RH per year. The resistive category (0.5 %RH/yr) fared slightly better than the capacitive category (0.8 %RH/yr). Individually, only one sensor (capacitive) had a drift rate (2.1 %RH/yr) in excess of 1% RH/year. This data suggests a minimal maintenance requirement for wall mount sensors.

Capacitive sensors, as indicated and/or suggested in the literature and specifications, are not particularly stable or accurate at high humidities. The upper end of the sensing range specified by the manufacturers ranges from 80 to 90% RH.

Resistive sensors, with an upper end sensing range of 95% RH, are recommended for use in duct high limit applications. In addition, the literature indicates that resistive sensors are less susceptible to contaminants. This suggests that resistive sensors would be the better choice in duct (high-limit) humidity sensing applications.

There appears to be no clear-cut set of specifications that one might use to distinguish the more accurate sensors from those that do not perform as well. It is recommended that commissioning include a sensor calibration check to verify conformance with the specification.

It would be valuable to perform similar tests on duct mounted relative humidity sensors.
Recommended relative humidity sensor specification:

1. Relative humidity instruments shall be rated for operation at ambient air temperatures within the range of 25 to 130 degrees F. The instrument sensing element shall be resistive or capacitive unless otherwise specified. The instrument transmitter shall be a 2-wire, loop-powered device and shall convert the sensing element signal to a linear 4-20 mAdc output over a range of 0 to 100 percent relative humidity. The instrument shall have a long-term stability corresponding to a drift rate not to exceed 1 percent relative humidity per year. The transmitter shall have zero and span adjustments.

1.1 In space or room sensing applications the instrument shall be designed to be wall mounted and be provided with all accessories to meet the application and mounting requirements. The instrument shall have an accuracy of plus or minus 3 percent over a range of 20 to 80 percent relative humidity.

1.2 In duct sensing applications the instrument shall have a resistive sensing element and shall be capable of being exposed to a condensing air stream with no adverse effect to the sensor calibration or other harm to the instrument. The instrument shall be provided with a duct probe and all accessories to meet the application and mounting requirements. The instrument shall have an accuracy of plus or minus 3 percent over a range of 20 to 95 percent relative humidity.

1.3 In duct sensing applications the instrument shall be installed no closer than 10 feet beyond the moisture injection mechanism.

1.4 Commissioning shall include a calibration accuracy check with the results documented in the Commissioning Report.

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METRIC CONVERSIONS:

degrees C = (degrees F - 32) / 1.8

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AUTHOR'S ADDRESS

US Army Corps of Engineers
Construction Engineering Research Laboratories
P.O. Box 9005

Champaign, IL 61826-9005
E-MAIL: d-schwenk@cecer.army.mil

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KEY

(To Sensor Manufacturers)

Resistive:

RH-1 = General Eastern
RH-2 = Elan Technical Corporation (ETC)
RH-3 = Temperature Control Specialties (TCS)

Capacitive:

RH-4 = Hy-Cal
RH-5 = Mamac
RH-6 = Vaisala